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Hegarty, Mary

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Department of Psychology
University of California, Santa Barbara
Santa Barbara, CA 93106

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Abstract

We examined individual differences in interacting and learning from diagrams, multimedia presentations and hypermedia instructional manuals and how these individual differences related to spatial abilities and knowledge. In several experiments, we found that comprehension of mechanical systems from static and animated diagrams was quite limited, and often resulted in misconceptions about how the systems worked. Students learned more from static and animated diagrams if they were augmented with verbal instruction, and students with high spatial ability and more background knowledge learned more from these multimedia presentations than students with low ability and less knowledge. In all of our experiments, learning from static diagrams and text was equivalent to learning from animated diagrams and commentaries, when these materials contained the same information. There was no evidence that different formats of instruction were more or less effective for individuals with different abilities and knowledge.

Final Report
Grant N00014-96-1-0525
Analysis and Synthesis of Hypermedia Visualizations
Mary Hegarty,
University of California, Santa Barbara

Note: This report is structured in the same format as ONR annual performance and progress reports. However the order of items are somewhat different. Each section contains relevant cumulative information over the entire project period of June 1 1997 to March 31, 2003.

1. Personal Information

PI Last name and first name: Mary Hegarty
Performing Institute: University of California, Santa Barbara

Mailing Address: Department of Psychology, University of California, Santa Barbara
City: Santa Barbara
State: CA
Zip Code: 93106-9660
Telephone: 805-893-3750
Fax: 805-893-4303
Email Address: hegarty@psych.ucsb.edu
Your website URL: http://www.psych.ucsb.edu/~hegarty/
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ONR Program Officer: Dr. Astrid Schmidt-Nielsen

2. Co-Principal Investigator

3. Long Term Goals of the Project

3.1 To examine how (1) spatial ability and (2) knowledge affect learning from diagrams, multimedia and hypermedia displays.

3.2 To examine individual differences in how people interact with hypermedia displays.

3.2 To translate this knowledge into practical guidelines for designing instructional materials for people of different abilities and expertise.

4. Scientific and Technical Objectives

4.1 To understand how people with different levels of spatial ability and expertise comprehend diagrams and multimedia displays in domains such as mechanics and what they learn from these displays.

4.2 To develop design principles for interactive displays in these complex domains and to build and evaluate prototypes embodying these principles.

5. Approach

5.1 Designing different versions of interactive and displays that explain how complex mechanical systems work.

5.2 Conducting empirical studies of how people interact with these displays, what they learn from them and from parts of the displays (e.g., static vs. animated diagrams), and the extent to which they can apply what they learned to make inferences and solve problems.

5.3 Examining the effects of individual difference variables such as spatial abilities and knowledge on how and what people learn.

6. Concise Progress Summary

In research conducted with funding from the Office of Naval Research in the last 6 years, we developed a model of how people understand and make inferences from multimedia presentations (Narayanan & Hegarty, 1998; 2002). The focus of the AASERT grant was to further test and develop this model by conducting empirical studies of how individuals with different amounts of spatial ability and knowledge comprehend and make inferences from these presentations. These studies involved collection and analysis of several different types of data, including measures of learning and comprehension, measures of how people interact with multimedia and hypermedia displays, response times, eye-fixation protocols, and verbal protocols. Most of our work was in the domain of mechanics

We conducted research on comprehension of three different types of materials:
1. Static and animated diagrams.
2. Multimedia presentations, including either static diagrams accompanied by text or animated diagrams accompanied by verbal commentaries.
3. Hypermedia instructional manuals that included static and animated diagrams, written text and aural commentaries.

6.1 Research on Comprehension of Diagrams

In one series of experiments, we examined what students learn from static and animated diagrams. Although the focus of the research project was on comprehension of multimedia and hypermedia displays, it was important to focus on comprehension of diagrams alone, because a theory of comprehension of multimedia presentations must include an account of the cognitive processes and comprehension outcomes that result from exposure to the individual media that make up multimedia presentations. This scientific account, in turn, can be the basis of a set of principles for the design of

multimedia presentations (cf. Narayanan & Hegarty, 1998; 2002), for example by specifying when and how diagrammatic materials should be augmented by text.

We conducted 4 experiments on comprehension of diagrams of mechanical systems. In **Experiment 1** we compared comprehension of a mechanical system after students studied a single static diagram of a mechanical system, a series of three diagrams that showed different phases in the operation of the mechanical system, and an animation of the mechanical system. Those who learned from 3 diagrams or an animation had better comprehension of the system than those who studied a single diagram, however there was no significant difference in comprehension between the 3-diagram group and the animation group (Kriz, 2002; Hegarty, Kriz & Cate, 2003). There were no effects of spatial ability on comprehension.

Experiment 1 therefore indicated limited effectiveness of an animation, in that studying a complete animation with about 140 frames lead to the same amount of understanding as studying 3 frames of the animation. The literature on animations (e.g., Tversky, Morrison & Betrancourt, 2002) suggested two possible reasons why our animation might not have been effective:
(1) The animation was not interactive, and it is possible that students comprehension outcomes could not keep up with the speed of the animation.
(2) The animation showed several components moving at once and there were no attentional cues to direct students' attention to the most important information.

We conducted 2 further studies in which we compared different types of animation to learning from a single static diagram. In **Experiment 2** we compared comprehension of an interactive animation, a non-interactive animation and a static diagram. Students who studied the animations had better comprehension than those who studied the static diagram, but there was no significant difference between comprehension of the two animations. In **Experiment 3** we compared an interactive animation with attentional cues, an interactive animation without attentional cues and a single static diagram. Again students who studied the two animations had better comprehension than students who studied the static diagram but there was again no difference in comprehension between the two animation groups. There were no effects of spatial ability, or interactions of ability with form of instruction in either experiment.

In **Experiment 4**, we monitored students' interactivity and eye-fixations while they studied interactive animations either with or without attentional cues. Examination of the interactivity data indicated that students used the interactivity provided. Examination of their eye fixations indicated that they were more likely to look at components of the animations when they were directed to these components by attentional cues. However there were no effects of either interactivity or attentional cues on their comprehension. Experiments 2-4 are currently being written up for publication along with some later research that was funded by a subsequent grant.

In a final experiment on comprehension of diagrams, we obtained preliminary eye-fixation evidence for mental animation as a strategy in mechanical troubleshooting.

Previous studies of mechanical reasoning suggest that people formulate a mental model of a mechanical system and are able to manipulate this model while reasoning about the system. Much as one can rewind or advance a video, people seem to be able to "play" a **causal** sequence of steps in their minds. This internal procedure has been dubbed 'mental animation' (Hegarty, 1992). Taking an embodied cognition approach, which suggests that our bodies are involved in cognitive processes, we proposed that eye movements can provide evidence for internal processes such as mental animation. This study analyzed eye movement data from seven subjects who learned about a flushing cistern from a computer animation. After viewing the animation, subjects were presented with troubleshooting questions that required them to think about the reasons why a breakdown would have occurred. While answering these questions, subjects were allowed to view a **static** diagram of the cistern in resting position. The eye movement data show distinct viewing patterns accompanying certain responses, including fixation patterns that mirror the movements presented in the computer animation. Furthermore, subjects often directed their gaze to empty spaces, where parts would have been had they moved. While talking, subjects did not simply look at the referent of their response. Rather, their eye movements indicate that they were imagining mechanical movement and not simply focusing visual attention on the part being discussed. These results suggest that subjects were using mental animation while reasoning about faults in the system; that while viewing a diagram, subjects were processing the static visual information in a dynamic manner. This research was presented at the European Eye Movement conference in 2003 (Kriz & Hegarty, 2003).

6.2 Research on Comprehension of Multimedia Presentations

Research on comprehension of diagrams alone indicated that diagrams lead to limited and often erroneous comprehension of how mechanical systems work. In another series of experiments, we examined comprehension of multimedia displays that included diagrams and accompanying verbal instruction.

In a series of four experiments (Hegarty, Narayanan & Freitas, 2002; Hegarty, Kriz & Cate, 2003) we examined the effects of learning from external computer animations and mental animation of static diagrams on people's mental models of a mechanical system. In three experiments, students learned how a mechanical system works from various instructional treatments including viewing a static diagram of the machine, predicting motion from static diagrams, viewing computer animations, and viewing static and animated diagrams accompanied by verbal commentaries. Although students' understanding of the system was improved by viewing both static and animated diagrams, there was no evidence that animated diagrams led to superior understanding of dynamic processes compared to static diagrams. Comprehension of diagrams was enhanced by asking students questions that required them to predict the behavior of the machine from static diagrams and by providing them with a verbal description of the dynamic processes. We concluded that predicting motion from static diagrams engages students' mental animation processes, including spatial visualization, and provides them with information about what they do and do not understand about how the machine works. Verbal instruction provides information that is not easily communicated in

graphics and directs students' attention to the relevant information in static and animated diagrams. Our research suggests that an understanding of students' mental animation abilities is an important component of a theory of learning from external animations.

In these experiments we examined the effects of spatial ability and prior knowledge of machines on comprehension of the various instructional media. While there were main effects such that those with high-spatial ability and more knowledge had superior comprehension outcomes, there was no evidence for aptitude-treatment interactions, i.e. that different formats of instruction were more or less effective for students with different abilities or knowledge.

6.3 Research on Comprehension of Hypermedia Instructional Manuals

Finally, in several experiments, we examined individual differences in learning from hypermedia instructional manuals that included several different sections aimed to address different phases in the comprehension of mechanical systems. These experiemtns were based on hypermedia presentations developed by Narayanan & Hegarty (1998; 2002) with funding from the parent grant. Details of the structure of these manuals are described by Narayanan & Hegarty, 2002).

We conducted several experiments comparing these hypermedia manuals to (1) informationally equivalent printed manuals (2) animations typical of extant research and commercial CD-ROMS, and (3) mixed-mode explanations extracted from commercial books. In all of these experiments we found main effects of spatial ability and prior knowledge in that students with more ability or knowledge tended to have better comprehension, but there were no interactions of individual differences with format of instruction. The most striking results of these experiments were that that manuals designed according to our guidelines were more effective than manuals that did not conform to these guidelines - both commercial and research products (Narayanan & Hegarty, 2002; Hegarty, Narayanan & Freitas, 2002).

In collaboration with researchers at the Applied Physics Laboratory, University of Washington, we conducted an additional experiment that investigated whether people learn more from multimedia presentations explaining how machines work if the presentations show realistic, 3d diagrams of the mechanical systems rather than 2D cross-sectional views. We had two professionally authored multimedia presentations built for testing. These manuals, one using 2D and the other using 3D graphics, explain a relatively complex but familiar device: the flushing cistern. In an experimental evaluation of these manuals at UCSB, we varied (1) whether students learned from the hypermedia manuals or merely from a labeled diagram of the machine and (2) whether they received 2-d or 3-d diagrams in their training. Results indicated that those who received the hypermedia visualizations had superior comprehension of the machine, but there was no difference between those who received 2-d and 3-d views. There were again no interactions of ability or knowledge with format of instruction.

Finally in an experiment on interactivity we compared the effects of guided versus

free navigation of our hypermedia manual on learning outcomes (Hegarty, Narayanan & Freitas, 2002). Results indicated no differences in comprehension between participants who were guided to view the sections of our hypermedia manual in an order prescribed by our design guidelines and those who were free to view the sections in any order. Moreover, there were few differences in how people in the guided and free navigation conditions actually interacted with the materials. Even those who were free to navigate the manual in any order tended to examine the materials in a linear order. In these experiments there were no significant effects of spatial ability on interaction with the hypermedia presentations.

7. Main Results/Best Accomplishments

We found that visual-spatial representations alone, including realistic, interactive animations, have limited utility for training novices about how machines work and that it is important to augment these representations with verbal instructions that draw people's attention to the relevant information in diagrams and describe non-visible entities (such as forces) that are not visible in realistic visualizations of machines.

In several experiments, we found that comprehension of mechanical systems from multimedia and hypermedia systems was better for students with high spatial ability than for students with low spatial ability. However there was no evidence that spatial ability interacted with the format of instruction, that is, there was no evidence that different formats of instruction were more or less effective for students with different abilities.

In all of our experiments, we found that learning from static diagrams and text was equivalent to learning from animated diagrams and commentaries, when these materials contained the same information. There was no evidence that different formats of instruction were more or less effective for individuals with different abilities and knowledge.

8. Impact/Applications

Consistent with much previous research (e.g. Mayer 1991; Hegarty &Just, 1993) our research suggests that visual-spatial representations need to be augmented with verbal instruction, especially when designing for novices. A new contribution of our research is to specify the specific ways in which verbal materials can augment comprehension. These are (1) to direct students attention to the most relevant information in the diagram (2) to guide them in "mentally animating" static diagrams and (3) to provide information about non-visible entities such as forces.

Our research provides no support for converting static printed materials to interactive computer presentations, including animations. We found no advantages of animated over static diagrams in our research and no advantage of interactive over non-interactive computer presentations.

Our research provides no evidence for aptitude-treatment interactions, i.e. that different forms of instruction are more or less suitable for students with different abilities or background knowledge. Students with higher spatial ability or more relevant background knowledge learn more from multimedia and hypermedia presentations in general, but ability does not interact with format of instruction.

9. Technology Transfer

Our main means of facilitating technology transfer has been through research presentations at forums attended by scientists and engineers including those from industry and military. Through various presentations we have disseminated the results of our research at cognitive psychology and education conferences.

We have also presented our research at workshops at the Naval Pacific Meteorology and Oceanography Center, San Diego, CA, and at ONR Workshops on Attention, Perception and Data Visualization.

This is a basic research project and therefore no actual products have been produced. However, our research has generated a set of guidelines for designing effective multimedia presentations which have been communicated through our publications and presentations.

11. Statistics

UCSB: Graduate Students/Postdoctoral scholars supported at least 25% from this grant for at least 1 quarter:

Graduate Students:
Non-minority women: 1
Minority woman: 2
Non-minority man: 1
Minority man: 1

12. Journal Articles

Hegarty, M., Kriz, S. & Cate, C. (2003). The Roles of Mental Animations and External Animations in Understanding Mechanical Systems. *Cognition & Instruction Cognition & Instruction, 21,* 325-360..

Hegarty, M., Quillici, J., Narayanan, N. H., Holmquist, S., & Moreno, R. (1999). Multimedia Instruction: Lessons from Evaluation of a Theory-based Design. *Journal of Educational Multimedia and Hypermedia, 8,* 119-150.

Narayanan, N. H. & Hegarty, M. (1998). On designing comprehensible hypermedia manuals. *International Journal of Human-Computer Studies, 48,* 267-301.

Narayanan, N. H. & Hegarty, M. (2002). Multimedia design for communication of

dynamic information. *International Journal of Human-Computer Studies, 57,* 279-315.

13. Books or Chapters

Hegarty, M. Narayanan, N. H. & Freitas, P. (2002). Understanding machines from multimedia and hypermedia presentations. In J. Otero, A. C. Graesser & J. Leon (Eds.). *The Psychology of Science Text Comprehension.* Lawrence Erlbaum Associates.

Kriz, S. (2002) Understanding simultaneity and causality in static diagrams versus animation. In M. Hegarty, B. Meyer & N. H. Narayanan (Eds.) (2002). *Diagrammatic Representation and Inference.* Proceedings of Diagrams 2002. Berlin: Springer.

14. Technical Reports

15. Presentations

Hegarty, M., Quilici, J., Narayanan, N. H., Holmquist, S., & Moreno, R. (1998, April) Designing hypermedia manuals to explain how machines work: Lessons from evaluation of a theory-based design. Hyped-Media to Hyper-Media: A Workshop at CHI'98: ACM SIGCHI Conference on Human Factors in Computing Systems, Los Angeles, CA.

Hegarty, M., Narayanan, N.H., Cate, C & Holmquist, S. (1999, July). Understanding Machines from Diagrams, Text and Hypermedia Presentations. Presented at the Annual Conference of the Society for Applied Memory and Cognition. Boulder, CO.

Kriz, S. (2002, April). Understanding simultaneity and causality in static diagrams versus animation. Paper presented at the Diagrams 2002 conference, Calaway Gardens, GA.

Kriz, S. & Hegarty, M. (2003, July) Staring into Space: Evaluating mechanical motion, mental animation and eye movements. Paper presented at the European Eye Movement Conference, Aberdeen, Scotland.

16. Patents Issued and Pending

None

17. Honors

Mary Hegarty was promoted from Associate Professor to Professor, effective July 1, 2000.

Mary Hegarty. Elected Fellow of the American Psychological Society, 2001.

18. Additional References (not listed above).

Hegarty, M. (1992). Mental animation: Inferring motion from static diagrams of mechanical systems. *Journal of Experimental Psychology: Learning, Memory and Cognition, 18,* 1084-1102.

Mayer, R. E. (2001). *Multimedia Learning.* New York: Cambridge University Press.

Tversky, B., Morrison, J. B. & Betrancourt, M. (2002). Animation: Can it facilitate? *International Journal of Human Computer Studies, 57,* 247-262.

19. Related Projects

Hegarty, M. Analysis and Synthesis of Hypermedia Visualizations Office of Naval Research 1997-2002, N000149610525.

Naryayanan, N. H. Eye Tracking Equipment for Analysis and Synthesis of Human Interactions with Hypermedia Information Visualizations, 2000-2001, $127,200, Defense Universities Research Instrumentation Program (DURIP) Grant managed by ONR.